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N_2 effect on GaAs etching at 150 mTorr capacitively-coupled Cl_2/N_2 plasma

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ABSTRACT

The role of N_2 on GaAs etching at 150 mTorr capacitively-coupled Cl_2/N_2 plasma is reported. A catalytic effect of N_2 was found at 20–25% N_2 composition in the Cl_2/N_2 discharges. The peak intensities of the Cl_2/N_2 plasma were monitored with optical emission spectroscopy (OES). Both atomic Cl (725.66 nm) and atomic N (367.05 nm) were detected during the Cl_2/N_2 plasma etching. With the etch rate and OES results, we developed a simple model in order to explain the etch mechanism of GaAs in the high pressure capacitively-coupled Cl_2/N_2 plasma as a function of N_2 ratio. If the plasma chemistry condition became positive ion-deficient at low % N_2 or reactive chlorine-deficient at high % N_2 in the Cl_2/N_2 plasma, the GaAs etch rate is reduced. However, if the plasma had a more balanced ratio of Cl_2/N_2 (i.e. 20–25% N_2) in the plasma, much higher etch rates (up to 150 nm/min) than that in pure Cl_2 (50 nm/min) were produced due to synergetic effect of neutral chlorine adsorption and reaction, and positive ion bombardment. Pure Cl_2 etching produced 14 nm of RMS surface roughness of GaAs. Introduction of $\geqslant$20% N_2 gas in Cl_2/N_2 discharges significantly reduced the surface roughness to 2–4 nm. SEM photos showed that the morphology of photoresist mask was strongly degraded. Etch rate of GaAs slightly increased from 10 to 40 nm/min when RIE chuck power changed from 10 to 150 W at 12 sccm Cl_2/8 sccm N_2 plasma condition. The surface roughness of GaAs etched at 12 sccm Cl_2/8 sccm N_2 plasma was 2–3 nm.

1. Introduction

Dry etching of GaAs has been extensively studied by many groups [1–22]. There have been a number of different types of plasma techniques employed for GaAs etching, including capacitively-coupled plasma (CCP) etching [1–6], electron cyclotron resonance (ECR) plasma etching [7–12], inductively coupled (ICP) plasma etching [13–16] and reactive ion beam etching (RIBE) [17,18]. Amongst these different techniques, CCP etching is the most common process due to the absence of expensive high density plasma sources and the turbomolecular pumps needed to achieve the low pressures required in high density processes. Typical high ion density processes operate at 1–10 mTorr, while conventional CCP etching occurs at 20–100 mTorr. Recently, we have found promising results at 150 mTorr capacitively-coupled plasma (HPCCP) etching for GaAs. We previously reported BCl_3/N_2 plasma etching at 150 mTorr [6]. This pressure regime can be achieved with a mechanical vacuum pump, which could lead to an even simpler hardware configuration for CCP systems.

The plasma etching of GaAs in Cl_2-based discharges is assumed to occur via a number of steps. Firstly, reactive neutral or ion species are generated in the plasma reactor. Secondly, the neutrals or ions have to be brought on the GaAs surface and react with Ga and As atoms after adsorption on the surface in order to make etch byproducts, such as $GaCl_3$ and $AsCl_3$. Thirdly, these etch byproducts are desorbed from the GaAs surface by ion assistance and evacuated through the vacuum system. A useful method for non-destructive plasma diagnosis and helping to understand the etch mechanism is optical emission spectroscopy (OES). OES can provide valuable information for relative peak intensities of plasma species, even though it does not yield quantitative data about plasma density [23]. The peak intensity data is very important to monitor the plasma and process condition during etching. With the background, OES is frequently used for end-point detection process [24].

In this paper, we report on a catalytic effect of N_2 at 150 mTorr CCP etching of GaAs in Cl_2/N_2 discharges and use OES as a tool for developing a simple model for the etch mechanism. It is also important to understand effect of etch parameter, which can cause a significant change of etch results. With the fixed chamber pressure at 150 mTorr, plasma gas composition and RIE chuck power are key process variables. Careful attention is paid to study gas composition effect on GaAs etch rate with the OES monitoring. We report photoresist damage and surface morphology with different gas composition, too. Etch rate and surface roughness is discussed as a function of RIE chuck power at the fixed 12 sccm Cl_2/8 sccm N_2 plasma composition.

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2. Experimental

A conventional capacitively-coupled plasma (HPCCP) system was used for the experiment [25]. The plasma power was supplied with a 13.56 MHz radio frequency power supply from Youngshin RF. The base and process pressure were maintained with a 600 l/min mechanical pumping module. The chamber diameter and height were 400 and 350 mm, respectively. The diameter of the RIE chuck was 150 mm. The base pressure was fixed at 30 mTorr and the process pressure employed was 150 mTorr. The flow rates of the gases were controlled by electronic mass flow meters. The total flow rate of Cl_2 and N_2 gases was fixed at 20 sccm (standard cubic meter per minute).

(1 0 0) oriented, semi-insulating GaAs samples were lithographically patterned with AZ 5290e photoresist. The samples were cut into $10 \times 10\ mm^2$ sections. The etch time was fixed at 5 min. After etching, the photoresist was removed with acetone. The etch depth was measured with a surface profilometry (Tencor alpha-step IQ).

Etched GaAs surface and photoresist morphology after etching was characterized with Scanning Electron Microscopy.

An optical emission spectroscopy (OES) was used to analyze the plasma species and their intensity during plasma etching. The OES system was SD 2000 model of Ocean Optics, Inc. Its hardware consists of an optical fiber, a CCD array and an A/D converter. The monitoring frequency range was 400–900 nm, and integration time was 100 m s.

3. Results and discussion

Fig. 1 shows the etch rates of GaAs and the $-$dc bias on the RIE chuck as a function of % N_2 in the capacitively-coupled Cl_2/N_2 plasmas. The total flow rate was fixed at 20 sccm. RF power was 150 W and the process pressure was 150 mTorr. Notice that pure 20 sccm Cl_2 discharges produced a low etch rate of 50 nm/min. The GaAs etch rate increased once 15% of N_2 was mixed with chlorine at the condition 17 sccm Cl_2/3 sccm N_2, and reached a maximum of 160 nm/min at 25% N_2. The etch rate of GaAs was reduced to $\leqslant$40 nm/min as the % N_2 was increased to 30–100% in the Cl_2/N_2 plasmas. GaAs was not etched at all at 100% N_2 (i.e. 20 sccm N_2) in the discharge. Therefore, the highest etch rate of GaAs was found at the 15 sccm Cl_2/5 sccm N_2 condition, which was about three times higher than with the pure 20 sccm Cl_2 plasma.

The negative DC bias was continuously increased with % N_2. At the two extremes of composition, namely 20 sccm Cl_2 and 20 sccm N_2, the dc biases were -100 and -400 V, respectively. However, the increase of $-$dc bias with increasing N_2 composition did not significantly affect the etch rate of GaAs. Similarly, the additional N^+ and N_2^+ ion bombardment did not accelerate GaAs etch rate for a % N_2 of $\geqslant$30% in the Cl_2/N_2 plasma. Therefore, the N_2-related plasma species played a role as a catalyst in increasing the GaAs etch rate only if the N_2 ratio was in the range of 15–25%.

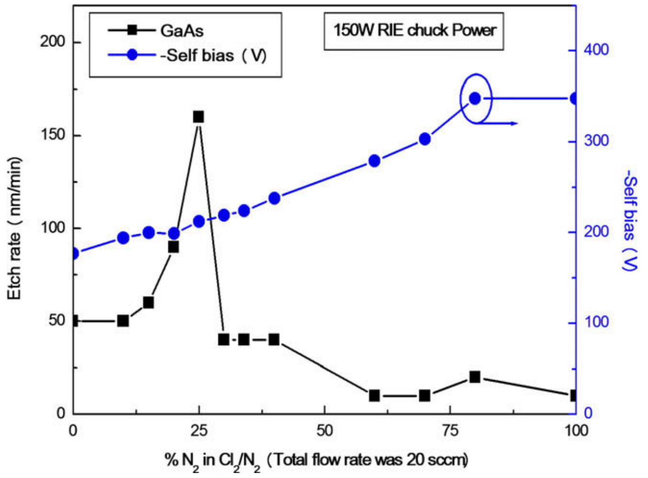

Fig. 1. GaAs etch rates and $-$self bias on the RIE chuck as a function of % N_2 at 100 W RIE chuck power, 150 mTorr and 20 sccm total flow rate.

The reason for the low etch rate of GaAs in the 150 mT chlorine discharges can be explained as following. The chlorine is an electronegative gas, so that, if a chlorine molecule collides with an electron, it can be easily dissociated into a negative ion and a radical neutral through the reaction shown in Eq. (1) [26].

$$Cl_2 + e^- \rightarrow Cl^- + Cl \quad (1)$$

The generation of the negative chlorine ions will reduce the free electron density in the discharge, leading reduction in the frequency of collisions between the electrons and the Cl_2 atoms, resulting in low plasma ion density. In addition, negatively-charged chlorine ions, Cl^-, will be repelled into the bulk plasma in the sheath region above the negatively-charged RIE chuck. The sheath region forms between the bulk plasma and the negatively-charged RIE chuck. The RIE chuck becomes negatively-charged relative to the bulk plasma in the presence of a plasma discharge in the chamber. The net result is that there will be less ion bombardment of chlorine ions on the GaAs surface, which will reduce the desorption rate of $GaCl_x$ and $AsCl_x$ on the GaAs, even though the neutral chlorine is still adsorbed and reacts with the GaAs atoms to make the etch byproducts.

Figs. 2–5 shows OES data for the 20 sccm Cl_2 (Fig. 2), 15 sccm Cl_2/5 sccm N_2 (Fig. 3), 8 sccm Cl_2/12 sccm N_2 (Fig. 4) and 4 sccm Cl_2/16 sccm N_2 (Fig. 5) plasmas. Note that both of the atomic chlorine peaks at 725.66 and 837.59 nm, and a broad range (400–550 nm) of molecular chlorine peaks were observed for the pure Cl_2 discharge in Fig. 2. Both atomic chlorine peaks and atomic nitrogen peaks were simultaneously observed in the 15 sccm Cl_2/5 sccm N_2 plasma. Recall that the GaAs etch rate reached its maximum value at this 15 sccm Cl_2/5 sccm N_2 gas composition. With a very high % N_2 in the Cl_2/N_2 plasmas, the OES intensity of the 725.66 nm chlorine peak decreased, and the magnitude of atomic nitrogen peak intensity became higher (Figs. 4 and 5).

Based on all of the etch results, $-$dc bias and OES data, we developed a simple model in order to explain the GaAs etch mechanism in the high pressure capacitively-coupled Cl_2/N_2 plasma (Fig. 6). Firstly, if there were only Cl_2 gas in the discharge, the negatively-charged chlorine ions would be dominant in the plasma. In this condition, the negatively-charged chlorine ions could be repelled from the sheath region to the bulk plasma, which would in-

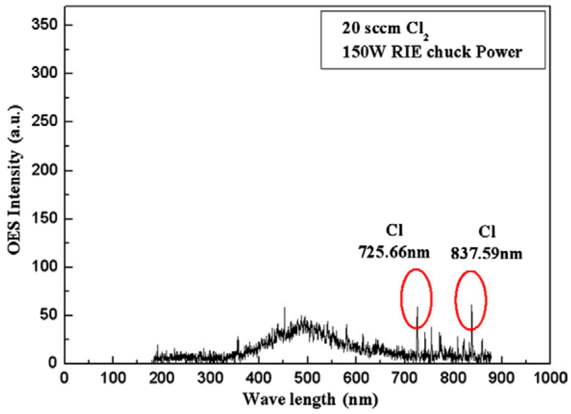

Fig. 2. OES intensity at 20 sccm Cl_2, 100 W RIE chuck power and 150 mTorr discharge.